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1501

A PRELIMINARY SET OF PARAMETERS FOR POPAE

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These tables of parameters have been developed for discussion at a POPAE Workshop in September 1974. They are calculated in rather low order approximation, and are subject to changes according to more careful and detailed analysis.

Contributions to this very preliminary design material from D. Edwards, L. C. Teng and others are acknowledged.

General Features

POPAE is a system of three storage and colliding rings, two superconducting for 1000 GeV (1 TeV) protons and one conventional for 20 GeV electrons. Luminosities are as high as $2 \times 10^{34} cm^{-2} \cdot s^{-1}$/interaction for proton-proton collisions and $3 \times 10^{32} cm^{-2} \cdot s^{-1}$/interaction for electron-proton collisions. The three rings are contained in the same enclosure.

The layout for POPAE considered here has the form of a racetrack - two circular sectors of a radius of about 960 m and two 1440 m long straight sections. Also two by-passes are added running parallel, to the outside, to the main straight sections 36 m apart. Each by-pass has a straight section 1025 m long.

No more than two beams at the time would run in each line. Beams would collide in two of the four lines, leaving the experiments on the other two lines in some sort of standing by.

The location of the racetrack with respect to the Main Ring is shown in Figure 1. The eastern long-straight sections run parallel to the power supply line, at the boundary of the Fermilab property at a distance of about 150 m. The racetrack is all contained between Wilson Road at the north and Butterfield Road at the south. The advantage of this location is that it leaves all the area at north and east available for the future expansion of the experimental lines which make use of the proton beam from either the Main Ring or the Energy Doubler.

The 1 TeV proton beam is extracted from the Energy Doubler at long-straight section B and injected in the clockwise proton storage ring. Another 1 TeV proton beam is extracted at the Energy Doubler long-straight section C and injected in the counterclockwise proton storage ring. The transport lines are circular sectors of a radius of about 800 - 1000 m and made of superconducting magnets. Alternatively, the beams might be extracted from the Main Ring at 400 GeV, stacked in the race-track and accelerated to 1000 GeV. In this case, the two transport lines can be made of conventional magnets.

The electron beam source can be the 300 MeV Linac used as CEA injector. The beam is injected counterclockwise in the Booster, accelerated up to 4 GeV, extracted and injected clockwise in the Main Ring, where finally it would be accelerated up to 10 GeV. For this operation, it is required to reverse the fields in the Booster and Main Ring. The electrons also are extracted at the long-straight section C and injected counterclockwise in the electron storage ring. They would be transferred by means of a string of conventional magnets located in the same tunnel used also to transport the protons. Once the beam is stacked up to the required intensity, then it would be accelerated to the final energy of 20 GeV.

The three rings would lie on top of each other. The three beam lines would then be separated by about 40 cm. The best arrangement seems to be:

counterclockwise	proton ring	bottom
clockwise	proton ring	middle
counterclockwise	electron ring	top

Table I

Proton Kinematic Parameters

Kinetic energy	400 GeV	1000 GeV
$B\rho$	13373.8 kG • m	33387.7 kG • m
$\beta(\equiv v/c)$	0.9999973	0.9999996
$\gamma(\equiv 1/\sqrt{1-\beta^2})$	427.32	1066.8
Circumference(Inject.)	9540.506 m	
Circumference(Stacking)	9540.356 m	
Average Radius(Inject.)	1518.419 m	
Average Radius(Stacking)	1518.395 m	
Curved Section Radius	964.515 m	
Revolution Frequency(Inject.)	31.423 kHz	
Revolution Frequency(Stacking)	31.424 kHz	
Revolution Time(Inject.)	31.824 μs	
Revolution Time(Stacking)	31.823 μs	
Transition Energy/$m_p c^2$ ($\equiv \gamma_t$)	30.5	
Betatron Tunes (ν_x & ν_y)	39.75	

Table II

A Proton Regular Cell (C)

Length (Stacking)	60.00224 m
Structure	(½QF)SBOBOBOBS(½QD)
	(½QD)SBOBOBOBS(½QF)
Bending Angle	3.5644° or 62.2098 mrad
Average Radius	964.515 m
Bending Magnets (B):	
No. per Cell	8
Length	5.89998 m
Bending Length	5.9 m
Bending Angle	0.4455° or 7.7762 mrad
Bending Field	17.63 kG (400 GeV)
	44.01 kG (1000 GeV)
Bending Radius	758.723 m
Sagitta	5.7 mm
Wedge Angle at Both Ends	0.2228°
Aperture	8(H) × 5(V) cm^2
Quadrupoles (F and D):	
No. per Cell	one QF and one QD
Length	1.8 m
Gradient	350.2 kG/m (400 GeV)
	874.4 kG/m (1000 GeV)
Aperture	8(H) × 5(V) cm^2
Phase Advance/Cell	90°
β min.	17.6 m
β max.	102.4 m
α min	0.414
α max	2.41
η min	1.21 m
η max	2.53 m
Drift Spaces: S	1.7 m
O	0.4 m

Table III

General Lattice

A. Inner Ring

Shape	Racetrack
Circumference (Inj.)	9540.506 m
Circumference (Stacking)	9540.356 m
Average Radius (Inj.)	1518.419 m
Average Radius (Stacking)	1518.395 m
No. of Superperiods	2

Each Superperiod is made of one Long Straight Section (LSS_i) and one Curved Sector (CS).

A Regular Bending Cell is denoted by C.

A Medium Straight Section (M) is half of a Regular Cell without Bending Magnets, with a drift space of 28.2 m between two regular quads.

Structure of CS	(4M) (45½C) (4M)
Structure of LSS_i	$M_u^* C_u^* (2C)\ A_i\ (2C) C_d^* M_d^*$

M_u^* is a M-cell with a regular dipole at the upstream end.

M_d^* is a M-cell with a regular dipole at the downstream end.

C_u^* is a regular half cell with a missing magnet at the upstream end.

C_d^* is a regular half cell with a missing magnet at the downstream end,

Long Drift Insertion (A_i):	
Length	1440.05 m
No. of equivalent Cells C	24
Total No. of Bending Cells	101
Total No. of equivalent Cells C	159

B. Outer Ring

It has the same structure of the Inner Ring, but with different Long Straight Section (LSS_o).

Structure of LSS_o	$\bar{M}_u^* (7\bar{M})\ (2\tfrac{1}{2}C)\ A_o\ (2\tfrac{1}{2}C)\ (7\bar{M})\ \bar{M}_d^*$

$\bar{M}_u^*$ and $\bar{M}_d^*$ are equal respectively to M_u^* and M_d^* but with reversed field (bending outward). $\bar{M}$ is equal to M but in one of the 7 $\bar{M}$ there is a regular bending magnet. The location of this bending magnet has to be chosen in order to make the difference in length between LSS_o and LSS_i equal to one RF wavelength λ on the injection orbit.

Table III (Cont'd)

λ (RF wavelength)	5.64527 m
Long Drift Insertion (A_o):	
Length	1025.68 m
No of equivalent Cells C	$17 + \lambda$
Transverse Separation	
between A_o and A_i	36 m

Table IV

Extracted Proton Beam Parameters

	Main Ring	Energy Doubler
Kinetic Energy	400 GeV	1000 GeV
Maximum Intensity	0.38 A (5×10^{13} ppp)	
Considered Intensity	76 mA (1×10^{13} ppp)	
No. of Bunches	1113	1112
Cycle	10 pulses/min	1 pulse/min
Vertical Emittance(*)	0.025 π mm•mrad	0.01 π mm•mrad
Horizontal Emittance(*)	0.025 π mm•mrad	0.01 π mm•mrad
Longitudinal Emittance	0.1 eV • s	
Bunching Factor	10	
Momentum Spread ($\Delta p/p$)	$\pm 0.84 \times 10^{-4}$	$\pm 0.34 \times 10^{-4}$
Bunch Separation	5.64527 m	
Total Pulse Length	21 μs	

(*) With a single-turn injection in the Booster. The emittances are extrapolated from measurements at 200 MeV and are defined to include 95% of the beam with gaussian distribution.

Table V

Proton RF Displacement Parameters

	400 GeV	1000 GeV
Injection Orbit Circumference	9,540.506 m	
Revolution Frequency (Inj.)	31.423 kHz	
Harmonic Number	1,690	
RF Frequency (Inj.)	53.105 MHz	
No. of Bunches Injected	1,113	1,112
No. of Missing Bucket	577	578
Fraction of Ring Filled	66%	
Single Bunch Area	0.1 eV · s	
Bunch Height ($\Delta E/E$)	$\pm$ 0.84 $\times 10^{-4}$	$\pm$ 0.34 $\times 10^{-4}$
Stationary Bucket Area	1.23 eV · s	3.375 eV · s
Stationary Bucket Height ($\Delta E/E$)	$\pm$ 1.50 $\times 10^{-4}$	$\pm$ 0.141 $\times 10^{-4}$
Moving Bucket Area	0.2 eV · s	
Moving Bucket Height ($\Delta E/E$)	$\pm$ 0.824 $\times 10^{-4}$	$\pm$0.303 $\times 10^{-4}$
Synchronous Phase	45°	60°
Linear Displacement (η = 2.55 m)	3.1 cm	
Energy Displacement	-4.874 GeV	-12.17 GeV
Peak Voltage/Turn	59.93 kV	56.22 kV
Energy Gain/Turn	-42.38 keV	-48.68 keV
No. of Revolutions during Displacement	115,007	250,000
Time for Displacement	3.66 s	7.96 s
RF Frequency Swing	814 Hz	694 Hz
RF Frequency Sweep	222.3 Hz/s	87.2 Hz/s
RF Turn-off Frequency Accuracy	$\pm$ 5 Hz	$\pm$ 2 Hz
Phase Oscillations Frequency	5.92 Hz	2.82 Hz
No. of Phase Oscillation	21.7	22.4

Table VI

Stack Parameters

	400 GeV	1000GeV
Mode of Stacking	At the Top	
Maximum No. of Cycles	207	443
Intensity	10 A	
No. of Cycles Required	200	
No. of Protons	2×10^{15}	
Linear Width (= 2.55 m)	9.6 mm	4.5 mm
Energy Spread ($\Delta E/E$)	$\pm 1.9 \times 10^{-3}$	$\pm 0.88 \times 10^{-3}$
Stacking Efficiency	0.7	0.6
No. of Protons/Pulse	1×10^{13} (76 mA)	
Filling Time/Ring	20 min.	3 h. and 20 min.
Horizontal Emittance (*)	0.025 π mm·mrad/0.01 π mm·mrad	
Vertical Emittance (*)	0.025 π mm·mrad/0.01 π mm·mrad	
Total Beam Width (max.)	12.8 mm	6.5 mm
Total Beam Height (max.)	3.2 mm	2.0 mm

(*) Emittances are defined to include 95% of the beam with gaussian distribution.

Table VII

P-P Luminosity and Limits

(a) 400 GeV × 400 GeV

Total Crossing Angle	1 mrad (vertical)
Vertical Emittance (95%)	2.5 π 10^{-8} m
Horizontal Emittance (95%)	2.5 π 10^{-8} m
Energy Spread ($\Delta E/E$)	$\pm$ 1.9 × 10^{-3}
$\beta^*_H = \beta^*_V$	1 m
η^*	0 m
$\sigma^*_x = \sigma^*_y$	0.065 mm
Beam Inetnsities ($I_1 = I_2$)	10A
Interaction Length	26 cm
Luminosity/Crossing	1.1 × 10^{34} cm^{-2} s^{-1}
Single-Beam Tune Shift(*)	-0.090
Beam-Beam Tune Shift	-0.0037

(b) 1000 GeV × 1000 GeV

Total Crossing Angle	1 mrad (vertical)
Vertical Emittance (95%)	1.0 π 10^{-8} m
Horizontal Emittance (95%)	1.0 π 10^{-8} m
Energy Spread ($\Delta E/E$)	$\pm$ 7.6 × 10^{-4}
$\beta^*_H = \beta^*_V$	1 m
η^*	0 m
$\sigma^*_x = \sigma^*_y$	0.041 mm
Beam Intensities ($I_1 = I_2$)	10A
Interaction Length	16 cm
Luminosity/Crossing	1.8 × 10^{34} cm^{-2} s^{-1}
Single-Beam Tune Shift(*)	-0.036
Beam-Beam Tune Shift	-0.0023

(*) A half-aperture of 2cm is taken into the calculations.

Table VIII

Acceleration of Protons from 400 GeV to 1000 GeV

Beam Intensity	10 A	
No. of Pulses in the Stack	200	
Stacking Efficiency	0.7	
Phase Space Area/Pulse/Bunch	0.1 eV · s	
Stack Phase Space Area/Bunch	28.6 eV · s	
Harmonic Number	1690	
Revolution Frequency	31.424 kHz	
RF Frequency	53.107 MHz	
Acceleration Time	30 s	
Magnetic Field Change Rate ($\dot{B}$)	0.88 kG/s	
Energy Gain/Turn	0.636 MeV	
Synchronous Phase Angle	2.43°	
Peak Voltage/Turn	15.0 MV	
Transition Energy/$m_p c^2$ ($\equiv \gamma_t$)	30.5	
Stationary Bucket Area	34.8 eV · s	(400 GeV)
	55.0 eV · s	(1000 GeV)
Stationary Bucket Height ($\Delta E/E$)	$\pm 3.6 \times 10^{-3}$	(400 GeV)
	$\pm 2.3 \times 10^{-3}$	(1000 GeV)
Moving Bucket Area	31.4 eV · s	(400 GeV)
	49.7 eV · s	(1000 GeV)
Moving Bucket Height ($\Delta E/E$)	$\pm 3.5 \times 10^{-3}$	(400 GeV)
	$\pm 2.2 \times 10^{-3}$	(1000 GeV)
Stack Energy Spread ($\Delta E/E$)	$\pm 1.9 \times 10^{-3}$	(400 GeV)
Average RF Power (*)	10 MW	
Phase Oscillations Frequency	103.3 Hz	(400 GeV)
	65.4 Hz	(1000 GeV)

(*) With an extra 50% dissipated in the cavity system.

Table IX

Electron Kinematic Parameters

Kinetic Energy	10 GeV	20 GeV
β ($\equiv v/c$)	1	1
γ ($\equiv 1/\sqrt{1 - \beta^2}$)	19,570.2	39,139.5
$B\rho$	333.577 kG · m	667.137 kG · m
Total Circumference	9540.356 m	
Average Radius	1518.395 m	
Curved Section Radius	964.515 m	
Revolution Frequency	31.424 kHz	
Revolution Time	31.823 μs	
Transition Energy/$m_e c^2$ ($= \gamma_t$)	30.5	
Betatron Tunes ($\nu_x \approx \nu_y$)	39.75	

Table X

10 GeV Electron Beam Parameters in the Main Ring

Kinetic Energy	10 GeV
β (=v/c)	1
γ $(= 1/\sqrt{1 - \beta^2})$	19,570.2
$B\rho$	333.577 kG · m
Bending Radius (ρ)	747.8125 m
Bending Field	446 Gauss
Quadrupole Field	5.977 kG/m
Betatron Tunes ($\nu_x \sim \nu_y$)	19.25
Average Intensity	10 mA
Total Circumference	6,283.185 m
Average Radius (R)	1,000 m
Revolution Frequency	47.713 kHz
Revolution Time	20.958 μs
Total No. of Electrons	1.31×10^{12}
Harmonic Number	10,017
RF Frequency	477.94 MHz
No. of Electrons/Bunch	1.31×10^{8}
Energy Loss/Particle Turn	1.18 MeV
Synchronous Phase Angle	30°
Peak RF Voltage/Turn	2.36 MV
RF Power (Average)* e	17.7 kW
Transition Energy/m c^2 ($= \gamma_t$)	18.75
Anti-Damping Factor ($R/\gamma_t^{\,2}\rho$)	0.0038
Phase Oscillations Frequency	1.45 kHz
Radiation Repartition Factors:	
J_z	1
J_x	0.9962
J_E	2.0038
Energy Damping Time	0.177 s
Vertical Damping Time	0.355 s
Radial Damping Time	0.357 s
Energy Spread (σ_E/E)	3.13×10^{-4}
Bunch Length (σ_τ)	0.097 ns
RMS Emittance (δ^2/β)	2.9×10^{-8} m
Repetition Rate	6 pulses/min.

(*) With an extra 50% dissipated in the cavity system.

Table XI

10 GeV Electron Beam Parameters in the Storage Ring

Kinetic Energy	10 GeV
β (= v/c)	1
γ (= $1/\sqrt{1-\beta^2}$)	19,570.2
$B\rho$	333.577 kG • m
Bending Radius (ρ)	758.723 m
Bending Field (B)	440 Gauss
Quadrupole Field	8.74 kG/m
Betatron Tunes ($\nu_x \sim \nu_y$)	39.75
Total Circumference	9540.356 m
Average Radius (R)	1518.395 m
Revolution Frequency	31.424 kHz
Revolution Time	31,823 μs
Transition Energy/$m_e c^2$ (= γ_t)	30.5
Harmonic Number	15,210
RF Frequency	477.94 MHz
Average Intensity/Pulse	10 mA
No. of Pulses	50
Average Full Intensity	330 mA
No. of Electrons/Bunch	4.39×10^9
Total No. of Electrons	6.68×10^{13}
Energy Loss/Particle/Turn	1.18 MeV
Synchronous Phase Angle	30^o
Peak RF Voltage/Turn	2.36 MV
RF power (Average)(**)	0.58 MW
Anti-Damping Factor ($R/\gamma_t^2\rho$)	0.0022
Phase Oscillations Frequency	0.71 kHz
Radiation Repartition Factors:	
J_z	1
J_x	0.9977
J_E	2.0022
Energy Damping Time	0.272 s
Vertical Damping Time	0.544 s
Radial Damping Time	0.546 s
Energy Spread (σ_E/E)	3.11×10^{-4}
Bunch Length (σ_τ)	0.08 ns
RMS Emittance (σ^2/β) (*)	0.40×10^{-8} m
Filling Time	10 min.

(*) On both planes, by assuming full coupling between the two modes of oscillations (k = 1). Also, the smooth approximation $\eta \sim \beta^{1/2}$ is used.

(**) With an extra 50% dissipated in the cavity system.

Table XII

20 GeV Electron Beam Parameters in the Storage Ring

Kinetic Energy	20 GeV
β (= v/c)	1
γ (= $1/\sqrt{1-\beta^2}$)	39,139.5
$B\rho$	667.137 kG • m
Bending Radius (ρ)	758.723 m
Bending Field (B)	880 Gauss.
Quadrupole Field	17.48 kG/m
Betatron Tunes ($\nu_x \sim \nu_y$)	39.75
Total Circumference	9540.356 m
Average Radius (R)	1518.395 m
Revolution Frequency	31.424 MHz
Revolution Time	31.823 μs
Transition Energy/$m_e c^2$ (= γ_t)	30.5
Harmonic Number	15,210
RF Frequency	477.94 MHz
Average Full Intensity	0.330 A
No. of Electrons/Bunch	4.39×10^9
Total No. of Electrons	6.68×10^{13}
Energy Loss/Particle/Turn	18.66 MeV
Synchronous Phase Angle	30°
Peak RF Voltage/Turn	37.33 MV
RF power (Average)(**)	9.24 MW
Anti-Damping Factor ($R/\gamma_T^2\rho$)	0.0022
Phase Oscillations Frequency	2.03 kHz
Radiation Repartition Factors:	
J_z	1
J_x	0.9977
J_E	2.0022
Energy Damping time	33.4 ms
Vertical Damping Time	66.8 ms
Radial Damping Time	67.0 ms
Energy Spread (σ_E/E)	6.22×10^{-4}
Bunch Length (σ_T)	0.06 ns
RMS Emittance (δ^2/β)(*)	1.6×10^{-8} m

(*) On Both planes, by assuming full coupling between the two modes of oscillations (k = 1). Also, the smooth approximation $\eta \sim \beta^{1/2}$ is used.

(**) With an extra 50% dissipated in the cavity system.

Table XIII

Electron Ring Lattice

It is identical to the Proton Ring Lattice.

Corresponding magnets have the same length. Field and gradient strength are already given in the Tables XI and XII. Dispersion and betatron functions are identical to the Proton Ring functions. A regular cell is the same as in Table II.

Total Beam Width (max.)	6.8 mm
Total Beam Height (max.)	2.6 mm
Bending Magnet Aperture	5(H) × 2(V) cm^2
Quadrupole Aperture	circular, 5 cm diameter

Table XIV

E-P Crossing, Luminosity and Limits

Proton Energy	400 GeV	1000GeV
Electron Energy	20 GeV	
Proton Intensity	10 A	
Average Electron Intensity	0.33 A	
Crossing Angle	1 mrad (vertical)	
$\beta_H^* = \beta_V^*$ (electrons)	0.2 m	
$\beta_H^* = \beta_V^*$ (protons)	1.0 m	
η^* (electrons and protons)	0 m	
$\sigma_x^* = \sigma_y^*$ (electrons(*))	0.057 mm	
$\sigma_x^* = \sigma_y^*$ (protons)	0.065 mm	0.041 mm
Interaction Length	24 cm	20 cm
Luminosity	$2.9 \times 10^{32} cm^{-2}s^{-1}$ /	$3.6 \times 10^{32} cm^{-2}s^{-1}$
$\Delta\nu_{ep}$ (electrons <u>on</u> protons)	3.9×10^{-4}	1.6×10^{-4}
$\Delta\nu_{pe}$ (protons <u>on</u> electrons)	0.014	0.029
$\Delta\nu_e$ (electrons, self-field)(**)	-0.06	
$\Delta\nu_p$ (protons, self-field)(**)	-0.090	-0.036

(*) On both planes, by assuming full coupling between the two modes of oscillations (k = 1). Also, the smooth approximation $\eta \sim \beta^{1/2}$ is used.

(**) A half-aperture of 2 cm is taken into the calculations

Table XV

Acceleration of Electrons from 10 GeV to 20 GeV

Beam Intensity	0.33A
Harmonic Number	15,210
Revolution Frequency	31.424 kHz
RF Frequency	477.94 MHz
Synchronous Phase Angle Before and After Acceleration	30°
Energy Gain/Turn	0.5 MeV
Acceleration Time	0.636 s
Magnetic Field Change Rate ($\dot{B}$)	0.69 kG/s
Peak Voltage/Turn	2.36 MV (at 10 GeV) 37.33 MV (at 20 GeV) programmed as $(\text{time})^{4}$ in between
Synchronous Phase Angle	45.39° (at 10 GeV) 30.89° (at 20 GeV) programmed accordingly in between
Extra Average Power for Acceleration (*)	0.25 MW

(*) With an extra 50% dissipated in the cavity system.


45 and ½ C
45 and ½ C
MASTER SITE P

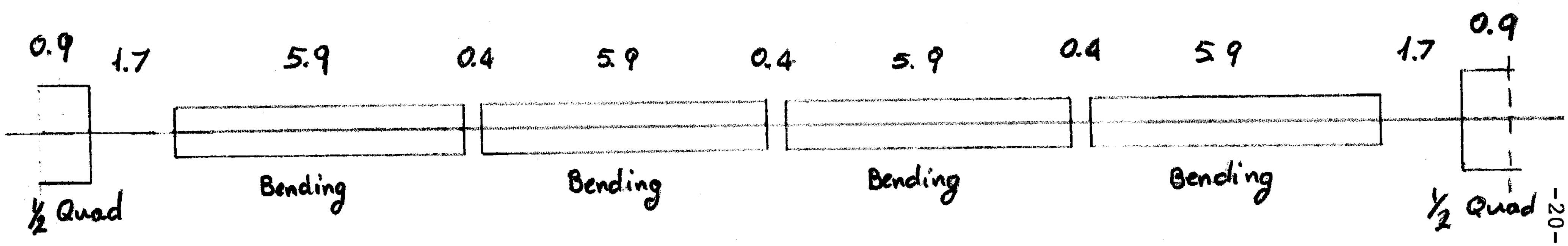
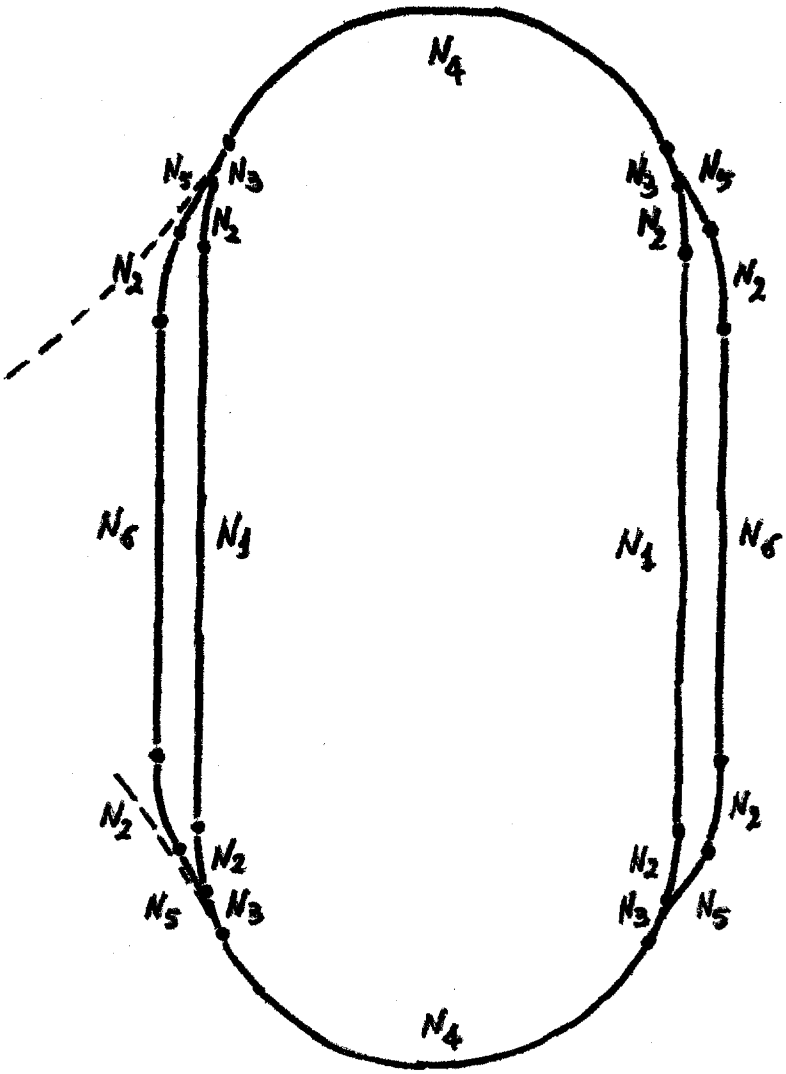


Fig. 2 - One Half of a Regular Cell
(Lengths are in meters)



$N_1 = 24$ Cells
$N_2 = 2 + 1/2$ Cells
$N_3 = 2 + 1/2$ Cells
$N_4 = 45 + 1/2$ Cells
$N_5 = 6$ Cells
$N_6 = 17$ Cells $+ \lambda$

Fig. 3 - Lay out with equivalent no. of Regular Cells (C)

$C \equiv 60.00224$ m
$\lambda \equiv 5.64527$ m

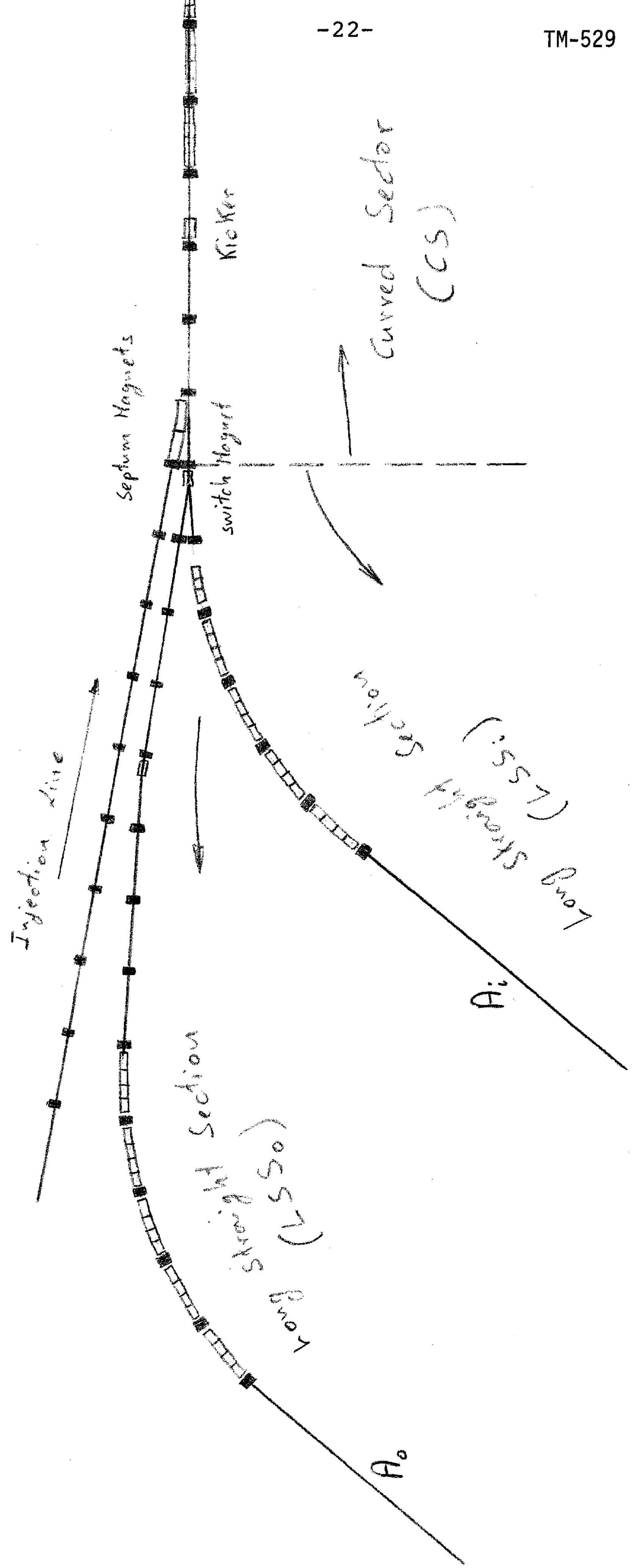


Fig. 4. Switching and Injection Area